Detection and Analysis of Near–Earth Object Encounters

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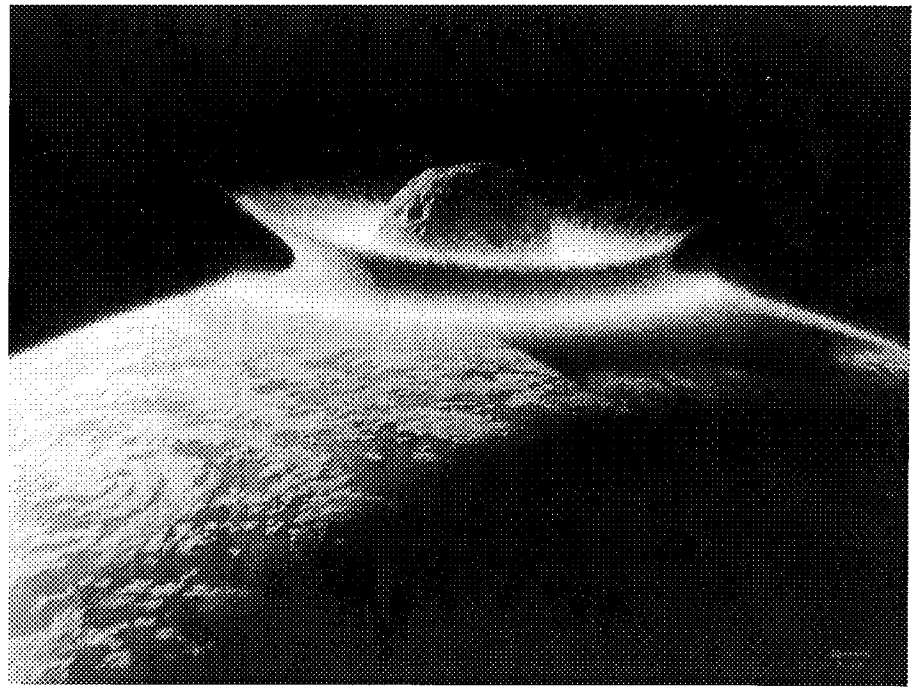

Minor Planet Amateur/Professional Workshop

Tucson, AZ

May 4, 2001

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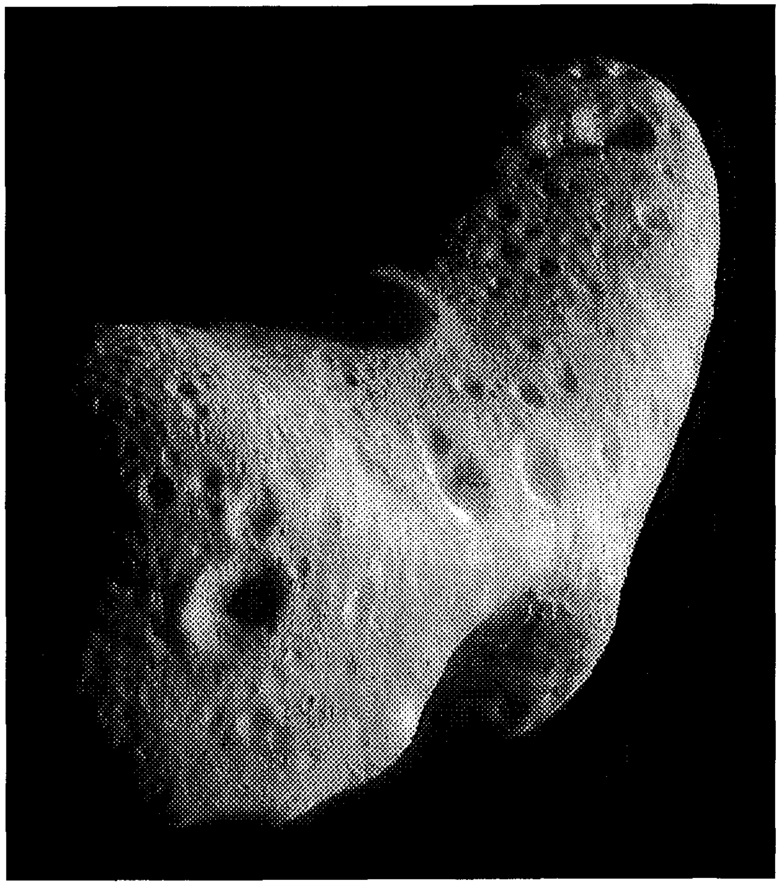
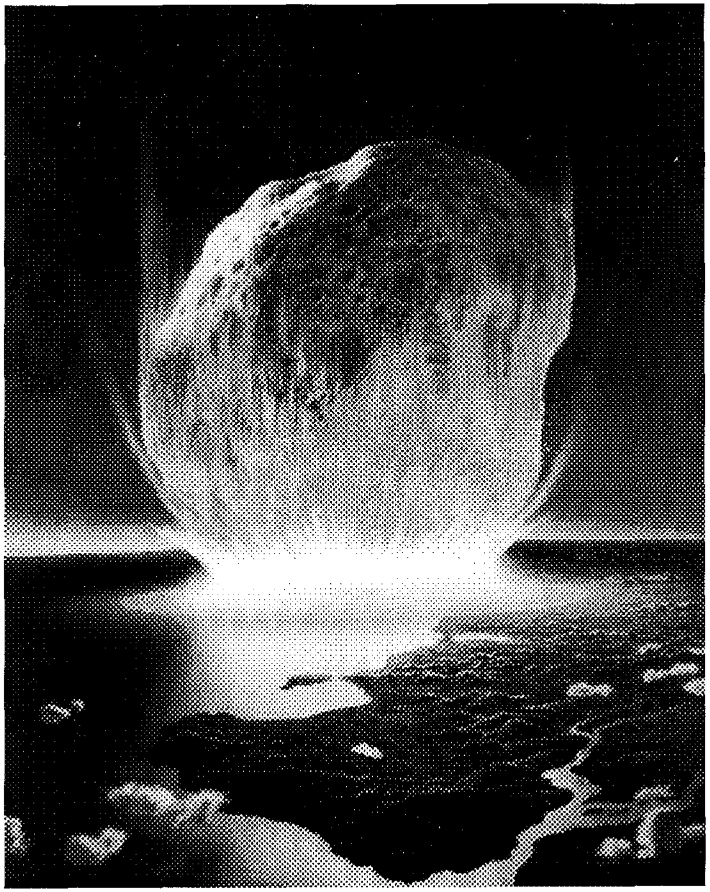
Outline

Encounter Detection

- Why we do it...
- How we do it...
  - Target plane methods
  - Linear encounter analysis
  - Nonlinear approaches
  - Pathological Cases
- Automatic systems



Why Bother?



Early discovery of threatening objects, coupled with early detection of potentially dangerous encounters is the key to mitigating a collision.

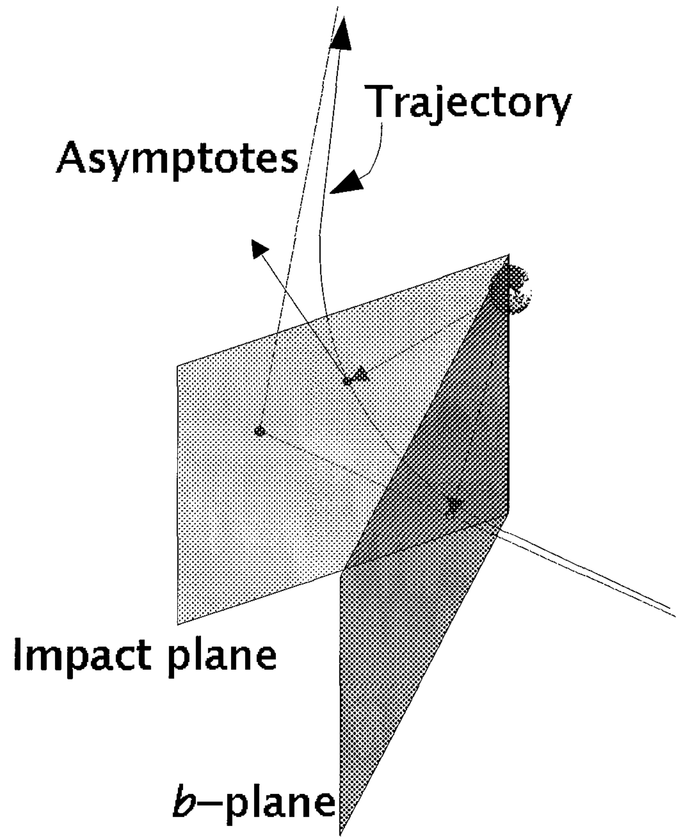
- Object detection does not imply collision warning.
- Monitoring along only the nominal trajectory is inadequate
- Warning time is crucial to mitigation effectiveness.

Historical Background

- Pre–1990's: Öpik theory, linear theory, Monte Carlo as an abstract concept.
- Shoemaker–Levy 9 (1994): Linear theory utilized and Monte Carlo approach successfully tested.
- 1997 XF_{11} (March 1998) : Linear theory sufficient to exclude 2028 impact, return problem proposed to deal with later encounters.
- 1999 AN_{10} (March 1999) : New theory based on understanding of resonant and nonresonant returns, experiments with new sampling methods. First potential impact using all data available, discovered and verified.
- 1998 OX_4 (June 1999): First lost potential impactor.
- Automatic Monitoring: Prototype running at Univ. of Pisa for 1 year has detected numerous potential impactors, but completeness unknown. More advanced systems presently under development at JPL and Pisa.

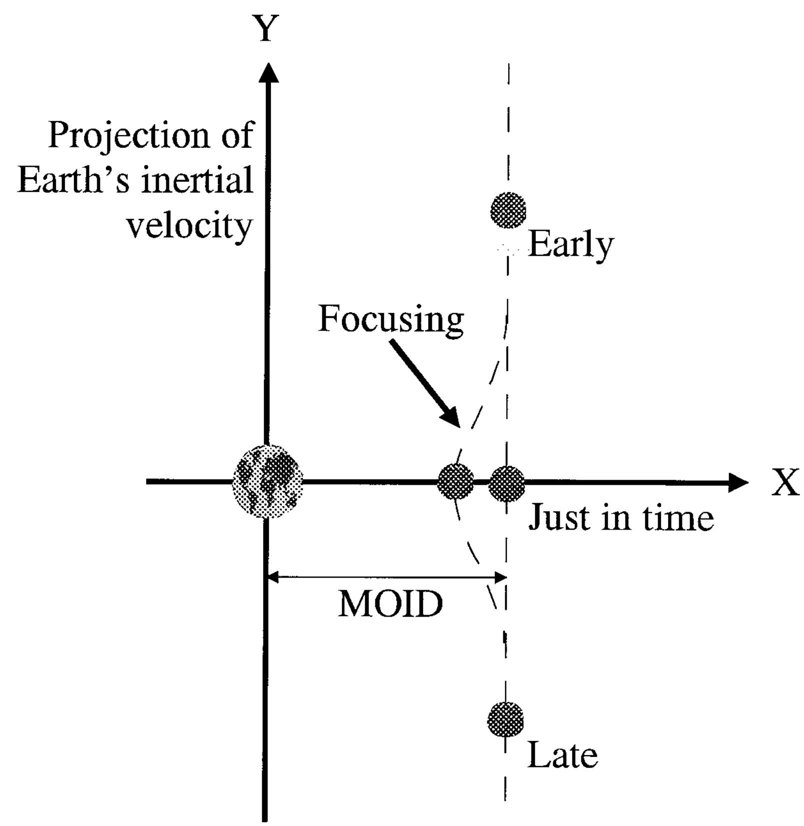
Target Plane Analysis

- *b*- plane (Öpik plane)
  - Orthogonal to incoming asymptote.
  - Preferred for low velocity encounters.
  - Hides gravitational focusing.
- Impact plane (Modified TP)
  - Orthogonal to geocentric velocity at perigee.
  - Only option for temporary capture encounters.



Target Plane Coordinates

- The coordinates on the target plane are arbitrary, but it is revealing to align with the heliocentric velocity of the Earth.
- Then we have the MOID, and the time error as the coordinates.
- MOID (Minimum Orbital Intersection Distance) is the minimum distance between the two orbital ellipses.



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Linear Encounter Analysis

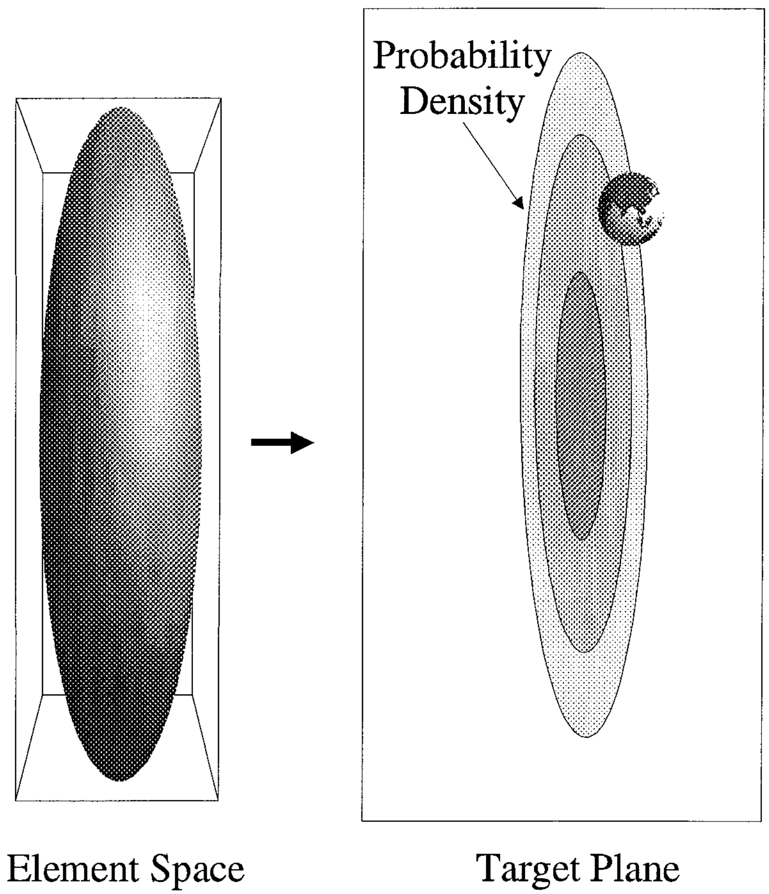
1) Start with orbital uncertainty at epoch of observations (6- D ellipsoid).

2) Propagate trajectory with variational equations to the target plane.

3) Map uncertainty onto target plane (2- D ellipse).

4) Compute impact probability by integrating the intersection of the Earth and the PD on TP.

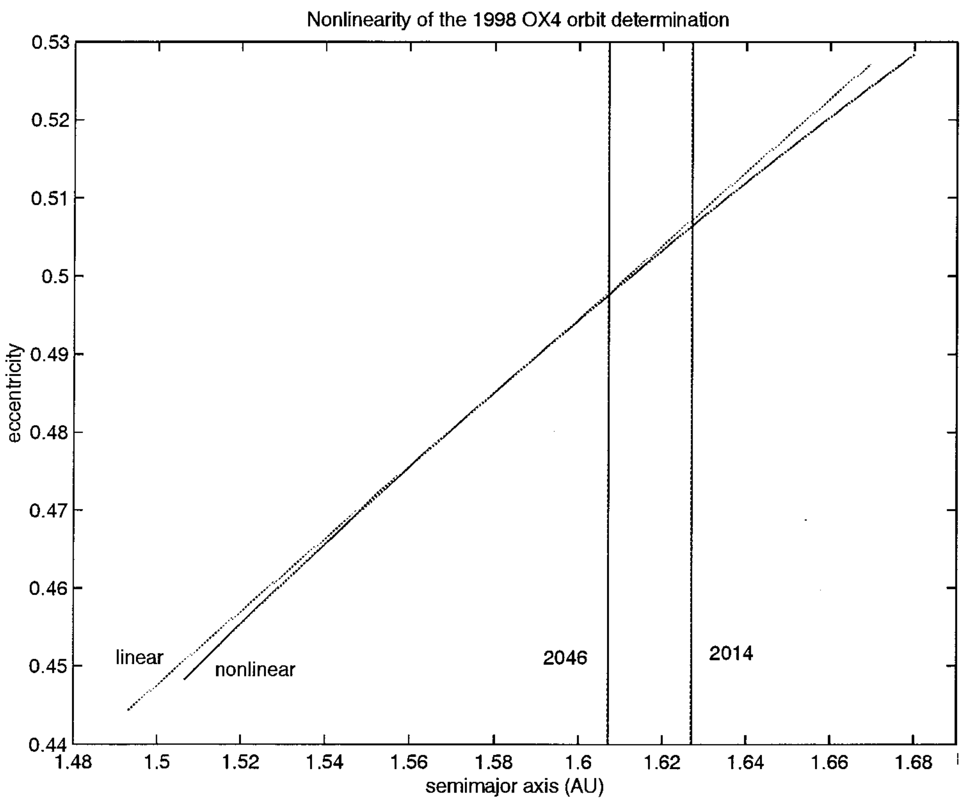
➔ Nominal trajectory must pass close to Earth, and uncertainty on TP must be small enough.

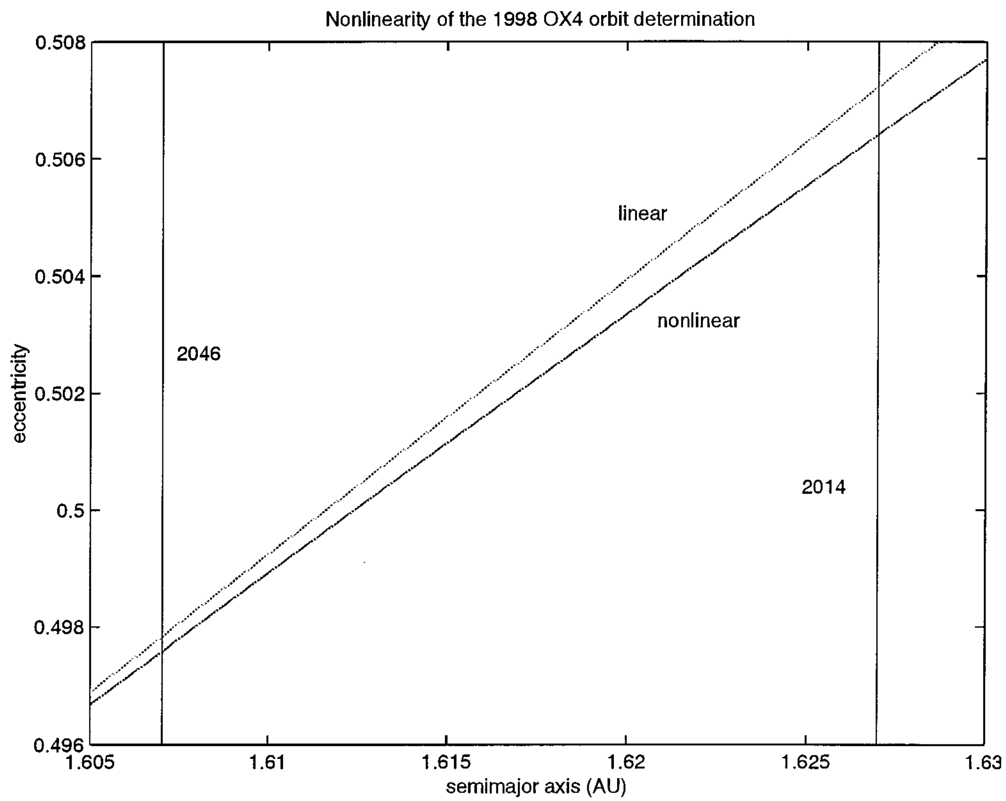


Limitations of Linear Approach

- The linear approach is "generally" adequate for...
  - Very near–term encounters with weak orbit determination.
  - Far–future encounters with well–determined orbits (if the trajectory is smooth enough).
- The linear analysis will be unreliable when...
  - There is a long propagation to the encounter. Nonlinearity induced from intervening encounters (and from Keplerian motion) can produce crazy results.
  - Orbit determination is poorly constrained: Initial ellipse becomes a "bananoid" when any axis grows very long.

1998 OX_4 Banananoid





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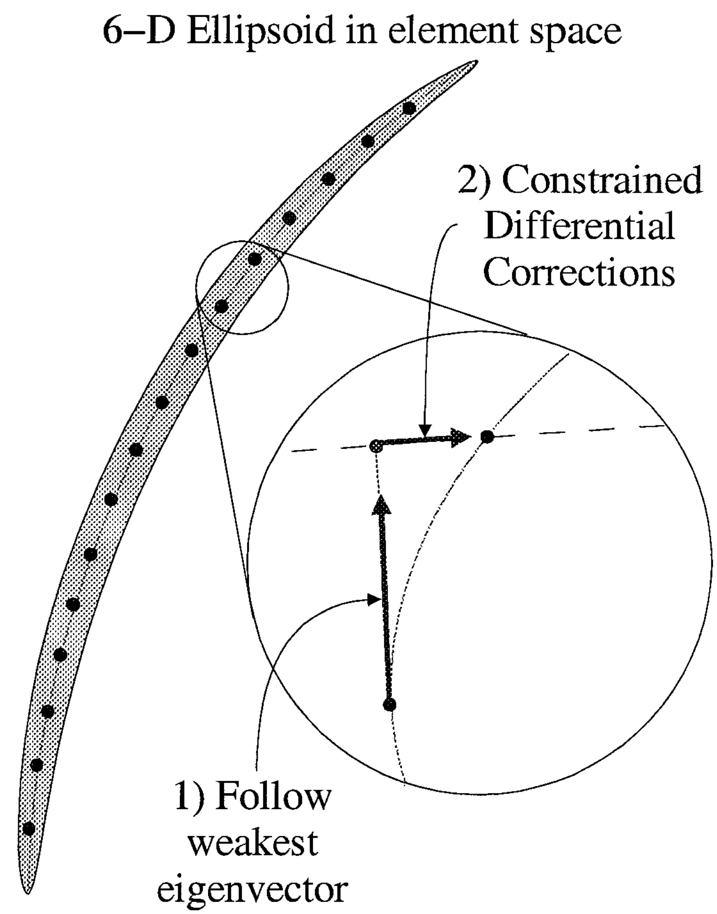
Line of Variations Sampling

- LOV sampling or "Multiple Solutions Method"
  - Sample the backbone of the ellipsoid by "following the river."
  - Provides 1–D sampling space, but information about the width of uncertainty is lost.
  - Simplifies TP analysis because different dynamical routes to the encounter are easy to distinguish.



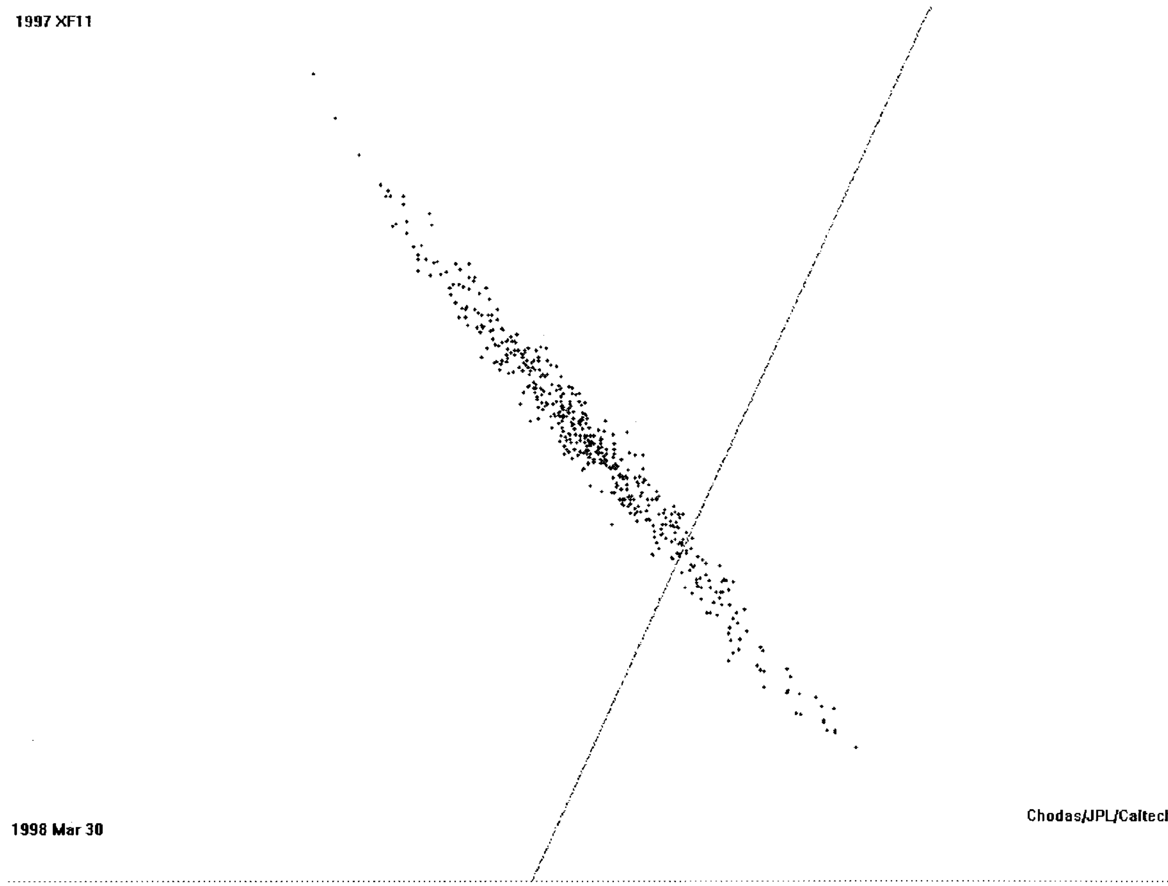
Monte Carlo Methods

- Careful sampling of the elements at epoch is necessary if the linear approach is inadequate. Two Monte Carlo methods are available:

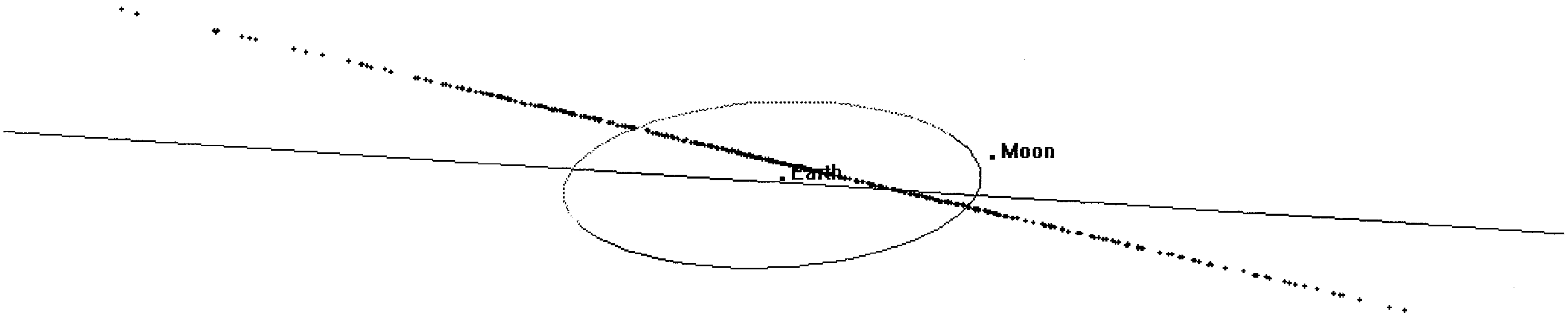
1) Sampling in element space.
    - *Assumes linearity (ellipsoid) in the orbit determination, but fully accounts for nonlinearity in propagation.*
    - *Sufficient unless orbit is very poor.*
2) Sampling in observation space
    - *Fully models all nonlinearities, but differential corrections for every sample is less efficient.*

1997 XF_{11} Monte Carlo Study

- Monte Carlo propagation with 500 points based on "88–day arc."
- Linear ellipsoid in Cartesian space at epoch of observations is a few Earth diameters in length.
- Ellipsoid is disrupted by encounter in 2028, leading to collision in 2040.



1997 XF11



2028 Oct 26.711

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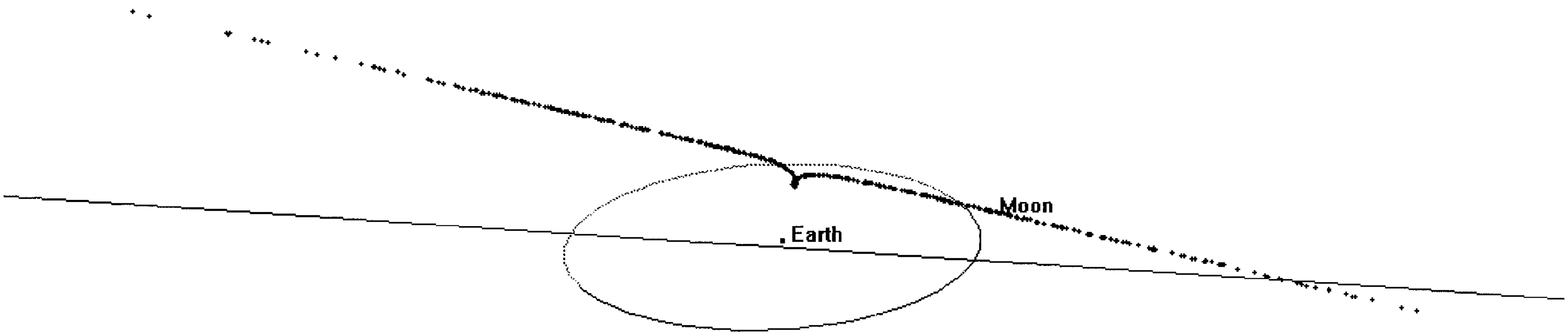
1997 XF11



2028 Oct 27

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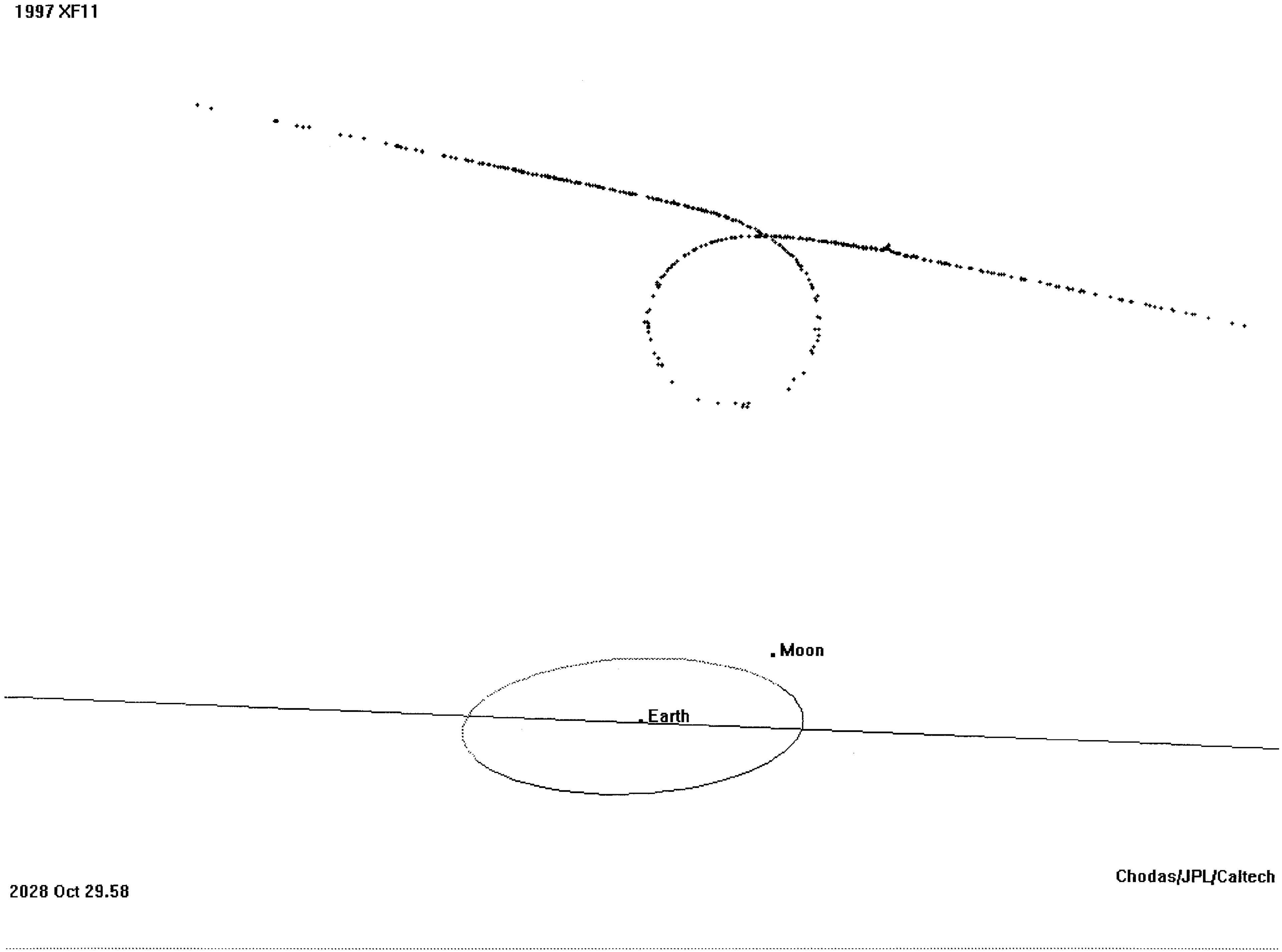
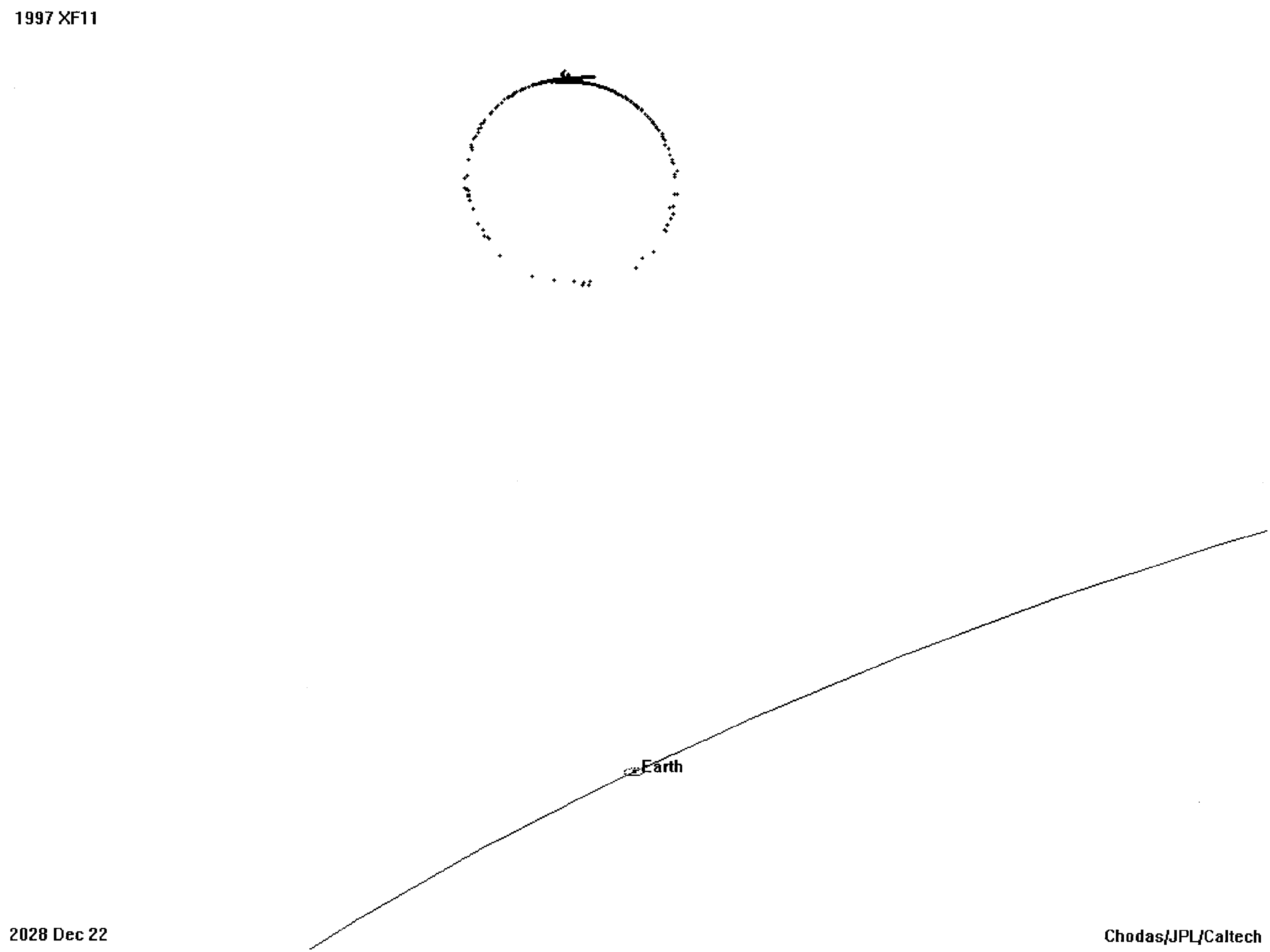
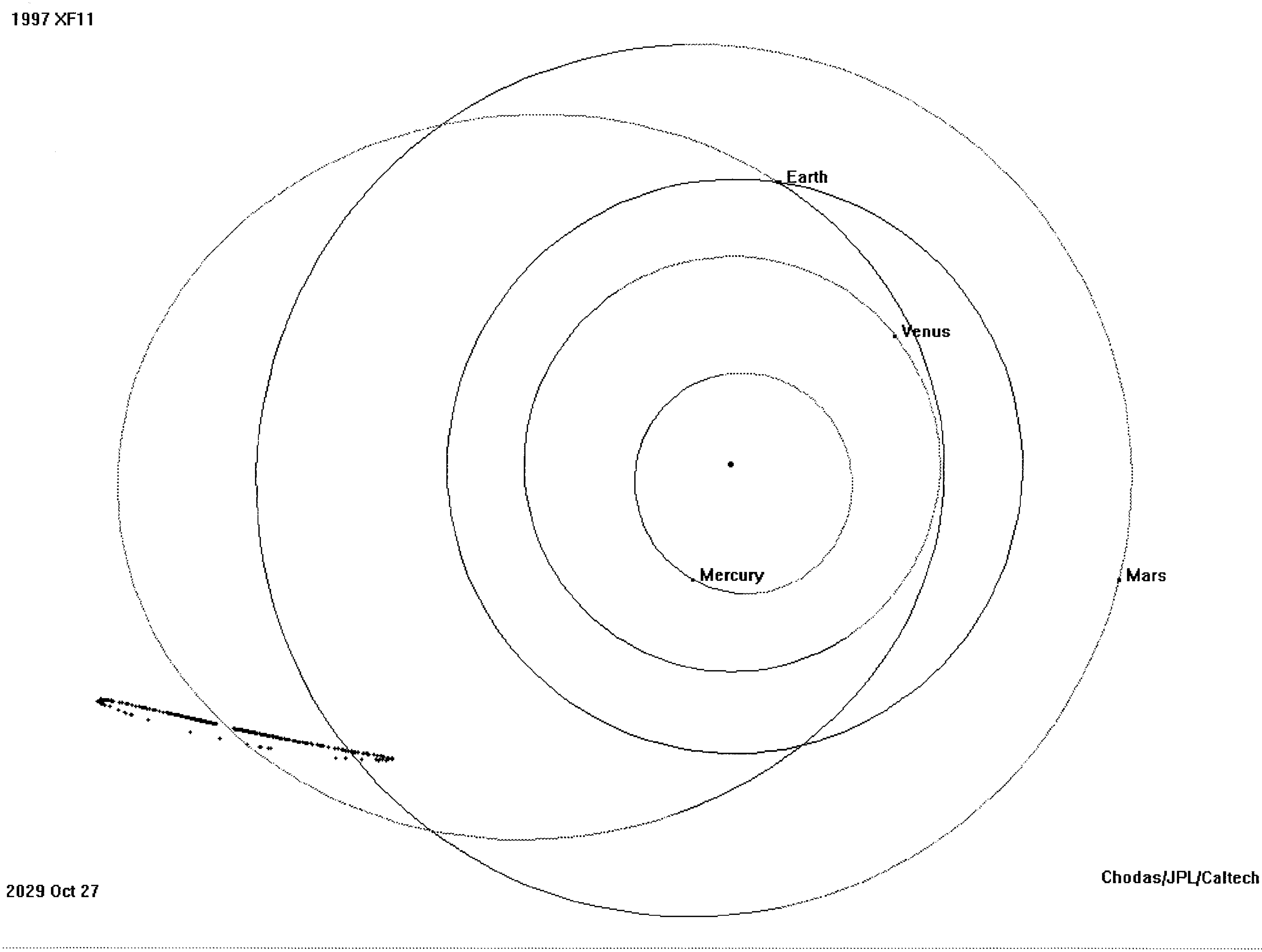
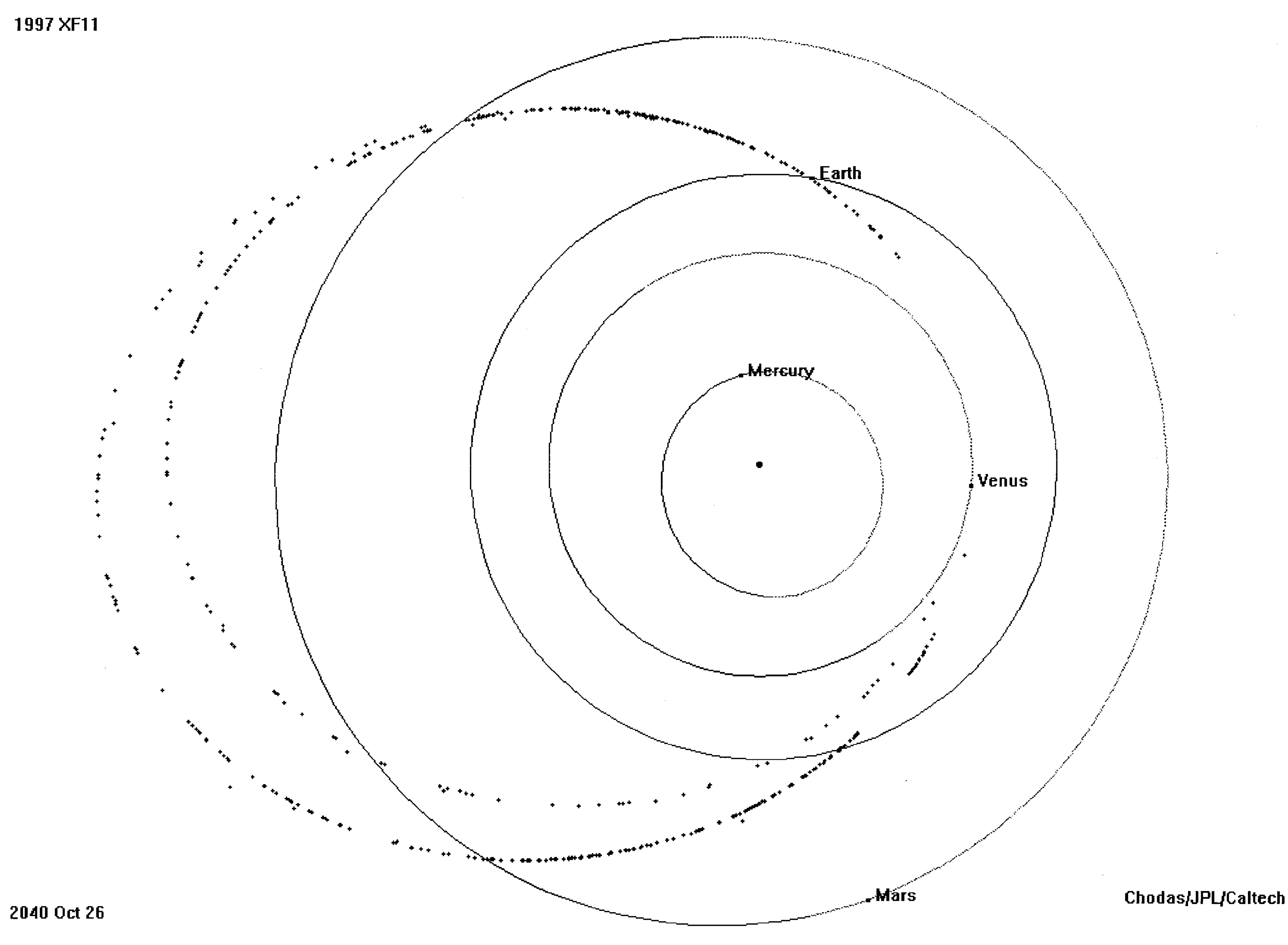
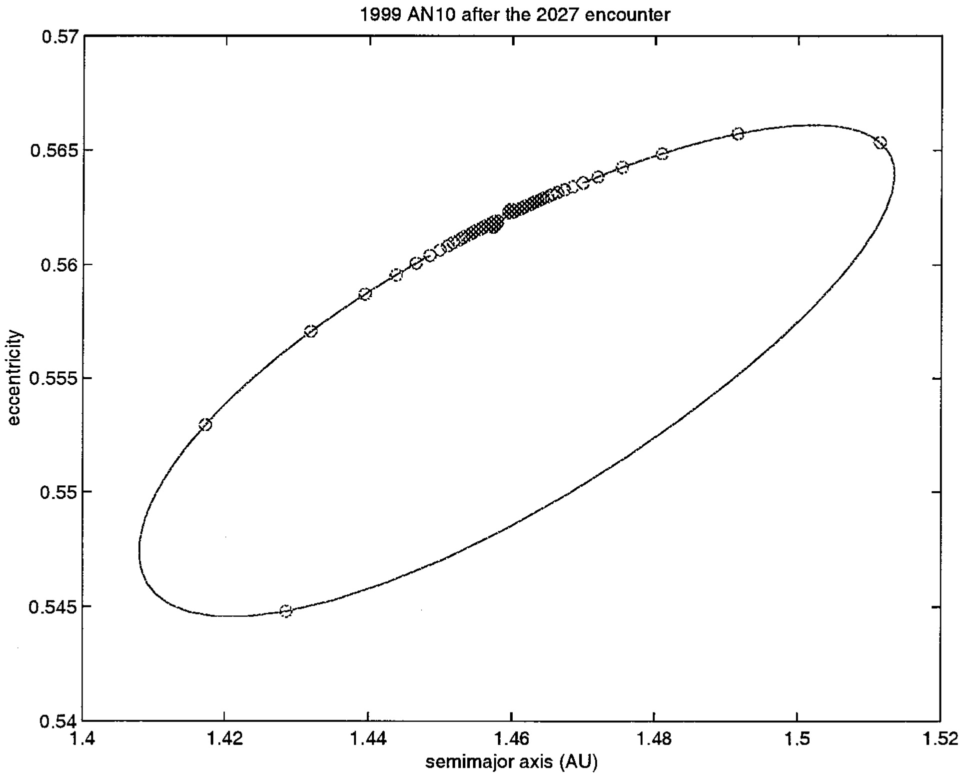

1997 XF11
Moon
Earth
2028 Oct 29.58
Chodas/JPL/Caltech

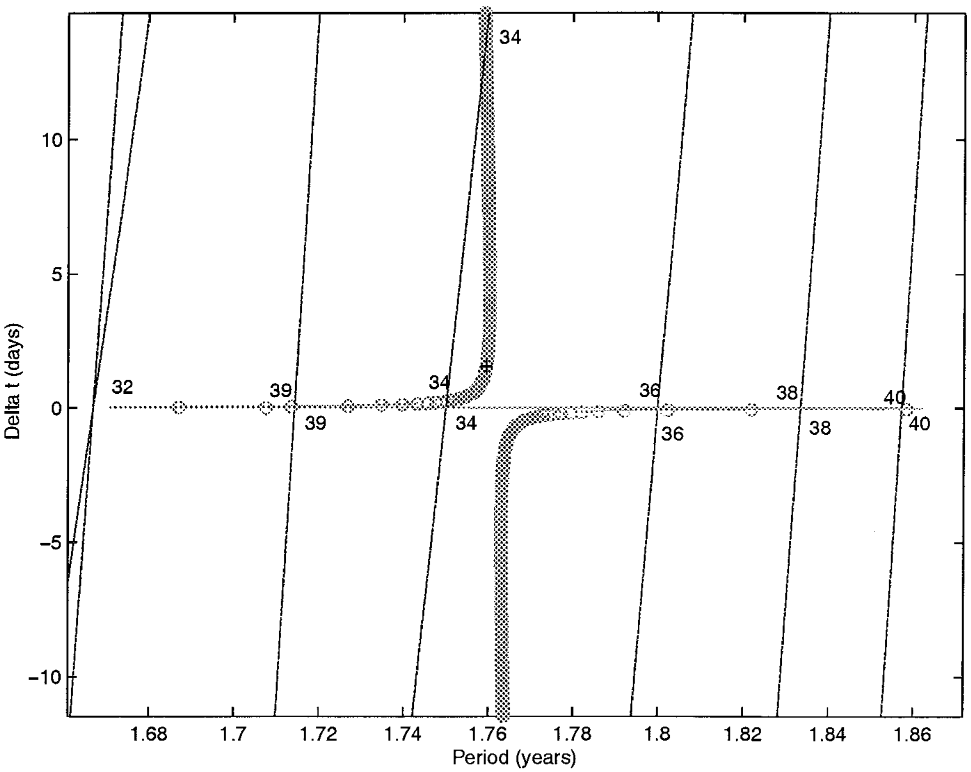

1997 XF11
Earth
2028 Dec 22
Chodas/JPL/Caltech


1997 XF11
Earth
Venus
Mercury
Mars
2029 Oct 27
Chodas/JPL/Caltech


1997 XF11
Earth
Mercury
Venus
Mars
2040 Oct 26
Chodas/JPL/Caltech

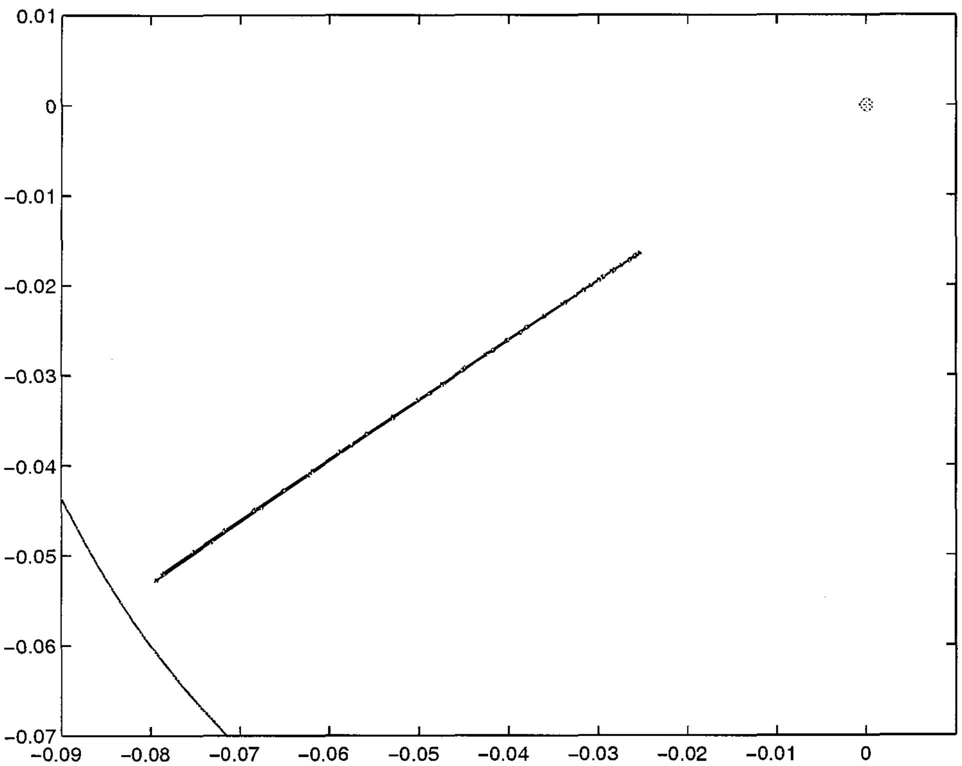
Resonant Returns



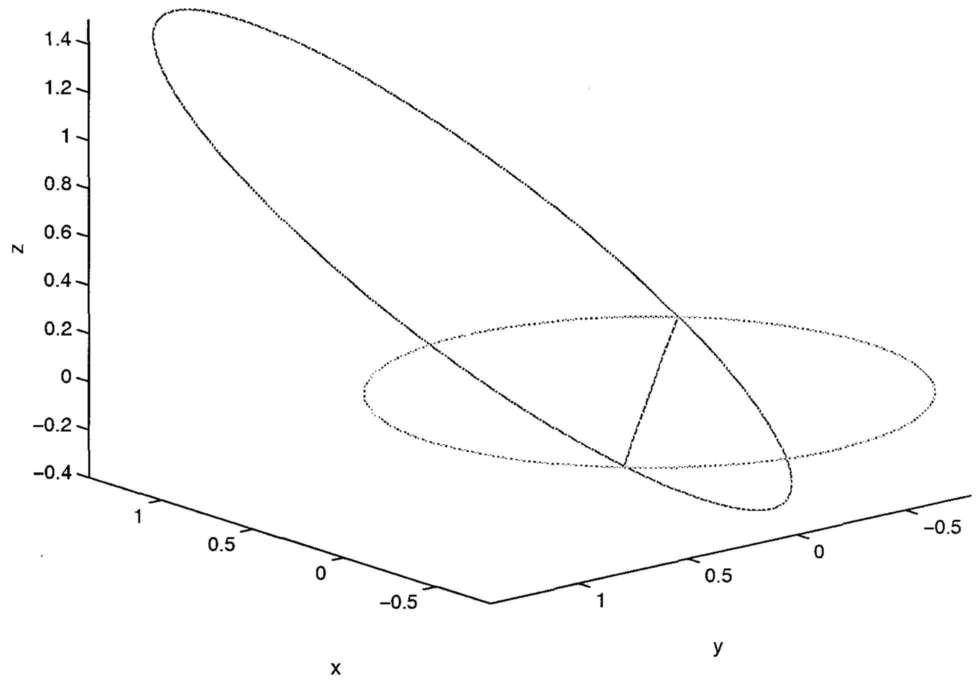


Problem Cases

Interrupted Returns



Non−resonant returns



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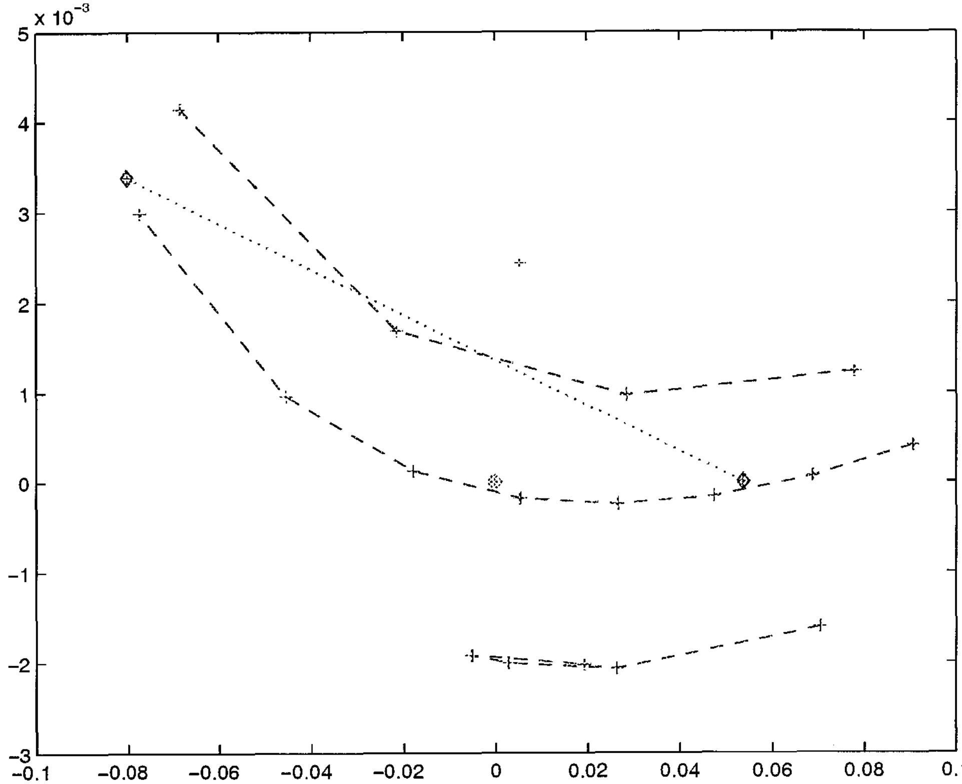
Complex Target Plane Analysis

- Consider a "Virtual Shower" from 1998 OX4 as an example.
- 20 LOV points intersect the TP within 0.1 AU in Jan. 2046:
    - *2 ordinary returns*
    - *1 interrupted return*
    - *1 singleton*
    - *1 sparse collision return*



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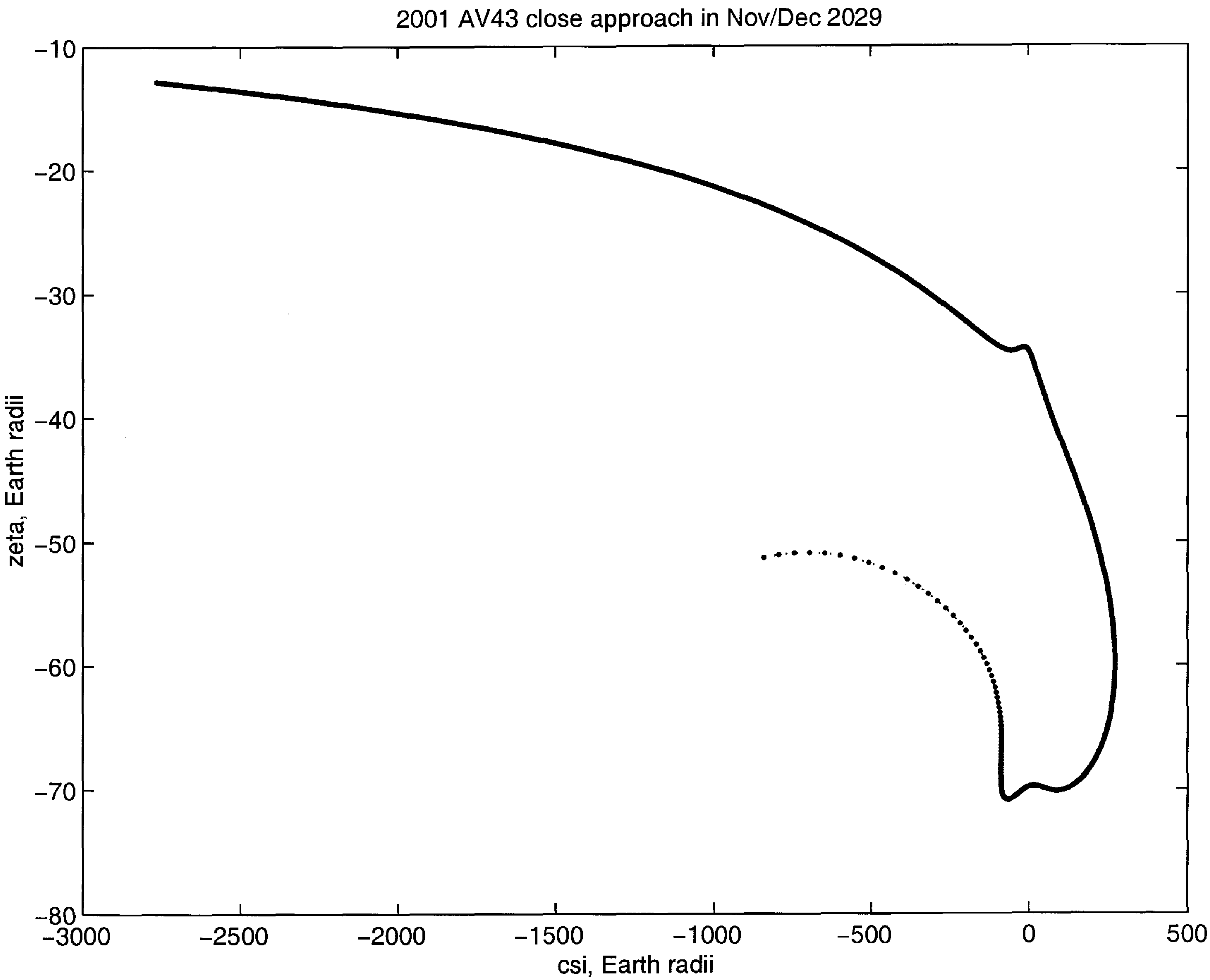
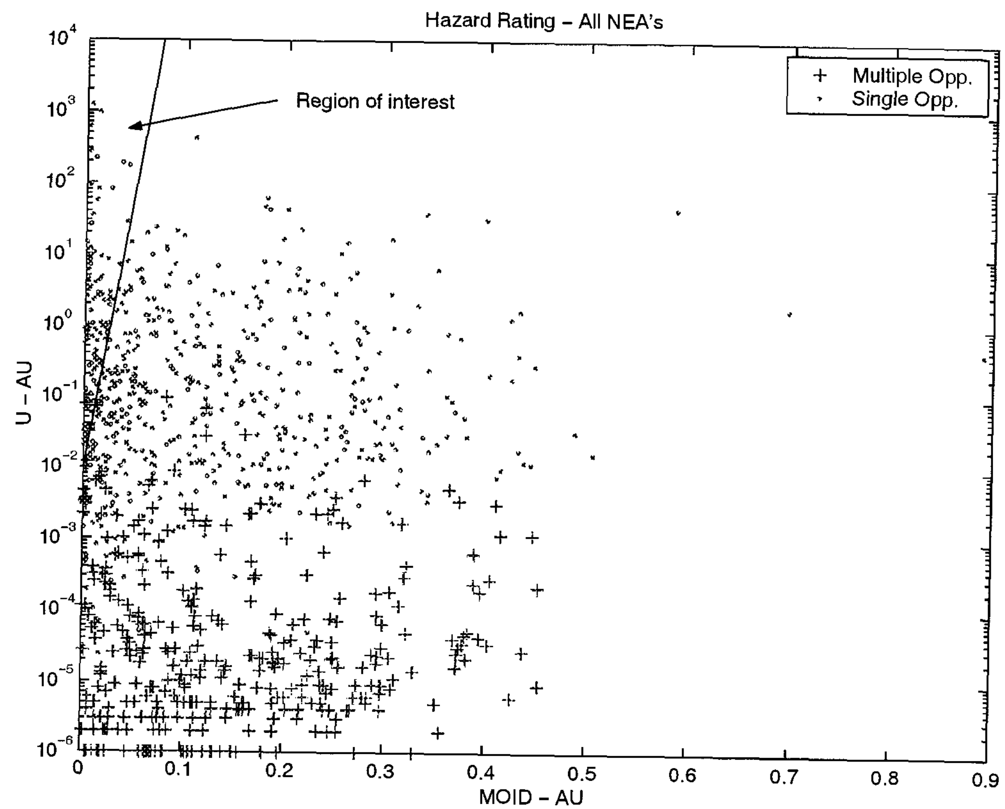

2001 AV43 close approach in Nov/Dec 2029
zeta, Earth radii
csi, Earth radii
−10
−20
−30
−40
−50
−60
−70
−80
−3000
−2500
−2000
−1500
−1000
−500
0
500

Automatic Monitoring Systems

- Discovery of first lost potential impactor led to recognition of need for continuous monitoring (1998 OX4).
- Monitoring requires a hierarchy of automation:

1) Observation files (updated several times daily)
2) Orbit Determination (when observations changes)
3) Linear Search (as far into future as feasible)
4) Nonlinear Search (as necessary, based on queuing system)



Redundant Systems

- Two independent and redundant systems are desired to maximize completeness and confidence.
- CLOMON (University of Pisa)
  - Detected dozens of "Virtual Impactors" in first year of operation.
  - Based on Impact Plane analysis along LOV (plus Newton's method).
  - "Mostly" complete for impacts with IP>10^{-6}.
  - System has led to improved understanding of pathological cases.
  - Several important improvements are in progress or planned.
- Sentry (Jet Propulsion Laboratory)
  - Based on *b*–plane analysis with hybrid LOV/Monte Carlo approach.
  - Presently under development and testing. Should be fully operational by fall 2001.